
Spectroscopic follow-up of Hot Jupiters

Research workshop on evolved stars

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Diploma in Physics: 10/2005-10/2010: Friedrich-Alexander University Erlangen-Nürnberg



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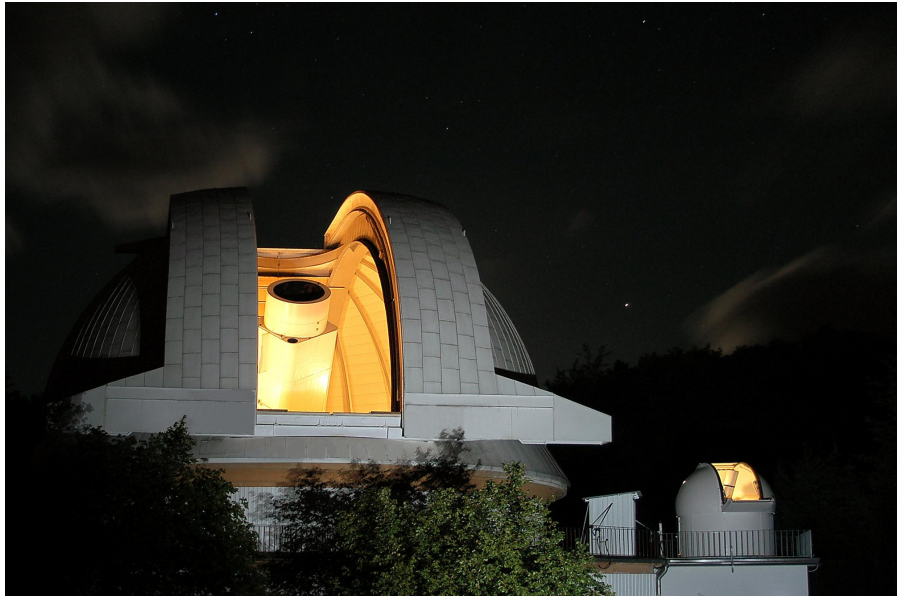
PostDoc: 03/2017-04/2018: Institute for Astronomy and Astrophysics, Tübingen



PostDoc: 05/2018-03/2023: Institute for Physics and Astronomy, Potsdam

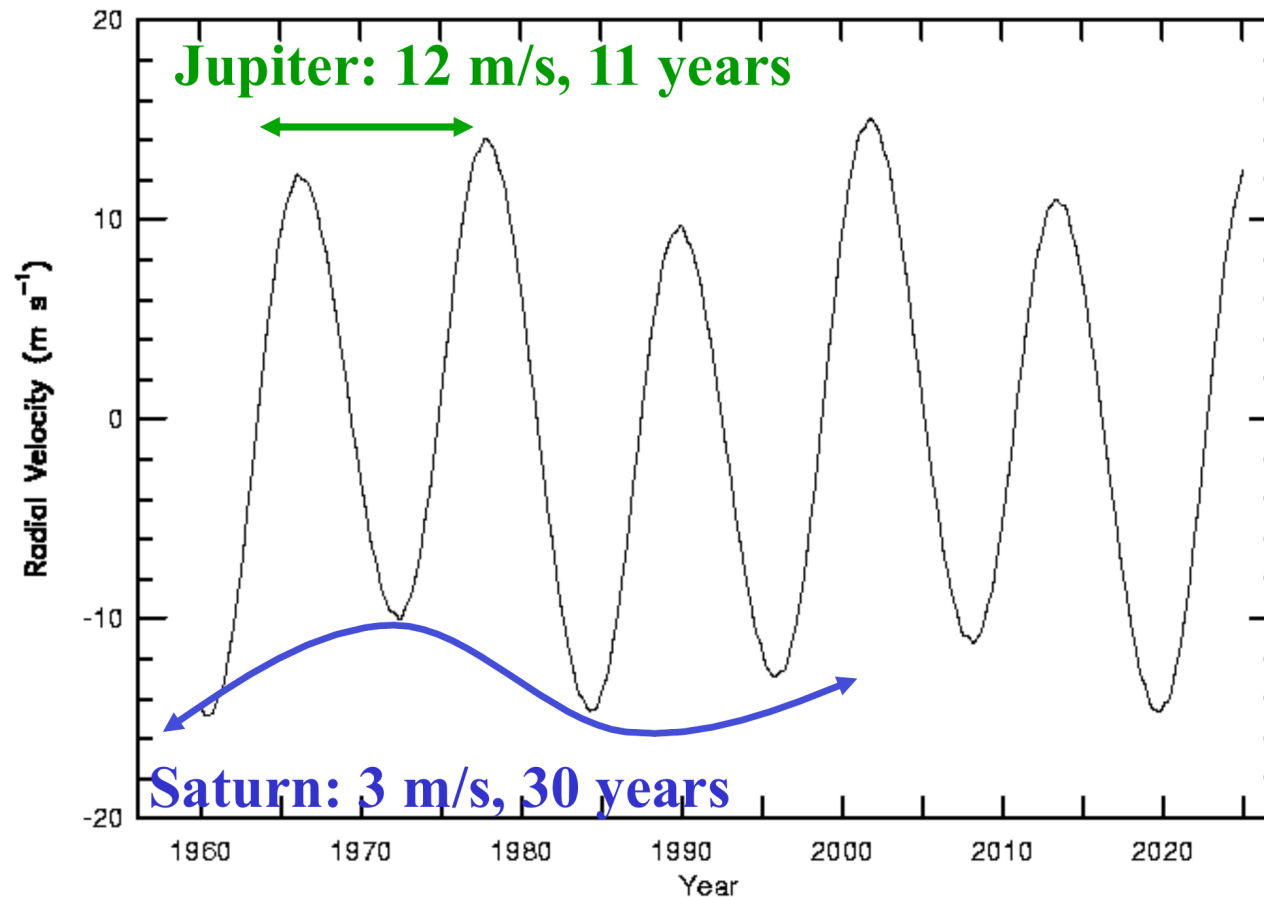


Staff scientist-today: 03/2025: Thüringer Landessternwarte Tautenburg



RV method

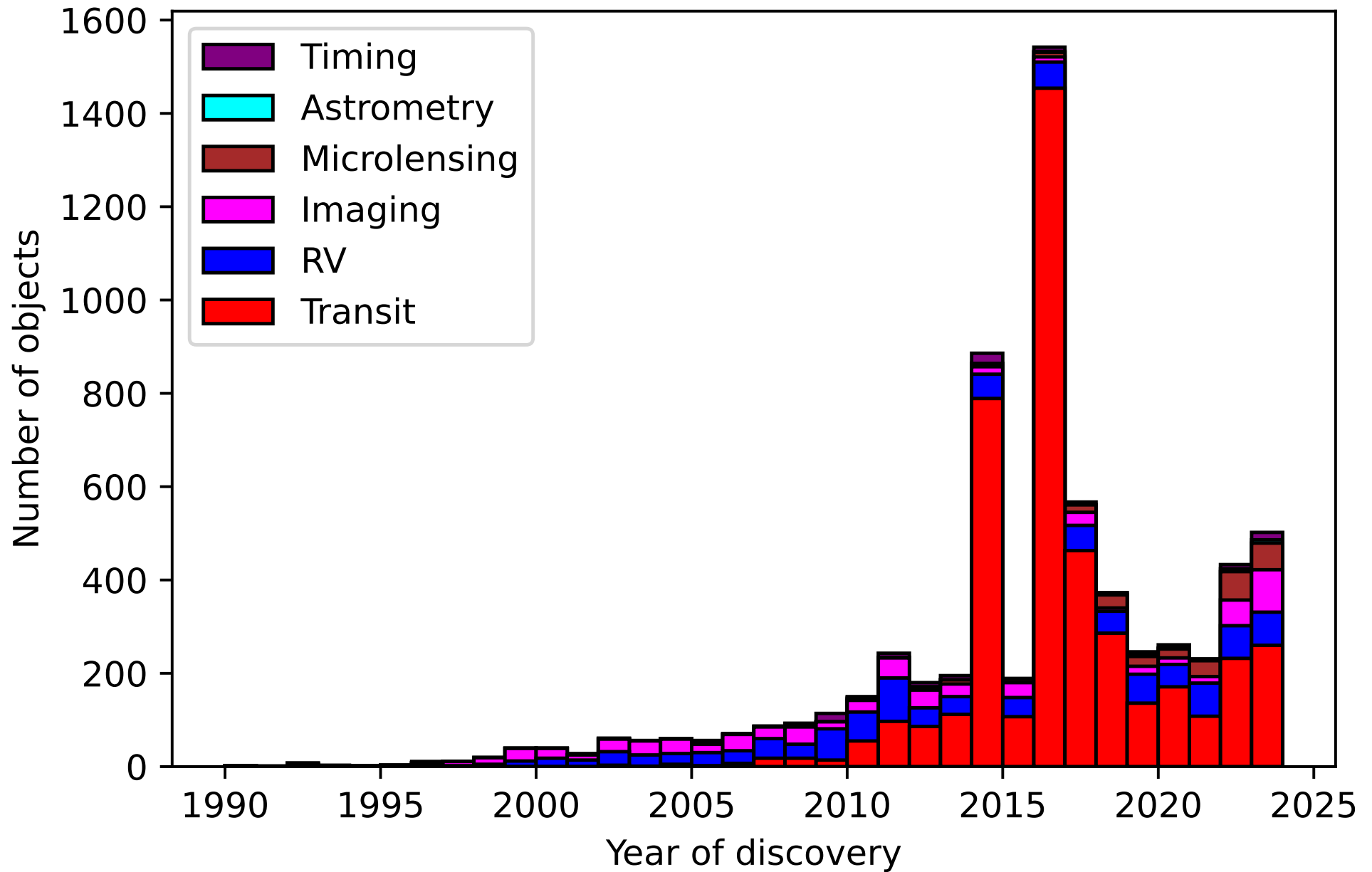
RV method measures the mass of the exoplanet



Requirements:

- Accuracy of better than 10 m/s
- Stability for at least 10 Years

Exoplanet Discovery Space



Mass determination of a planet in an (exo-)planetary system

planet is invisible, so we can only measure the velocity of the star about the center of mass of the system

Using:

- Circular Orbit
- Star is much more massive than the planet

$$V_{\text{obs}} = \frac{28.4 m_p \sin i}{P^{1/3} m_s^{2/3}}$$

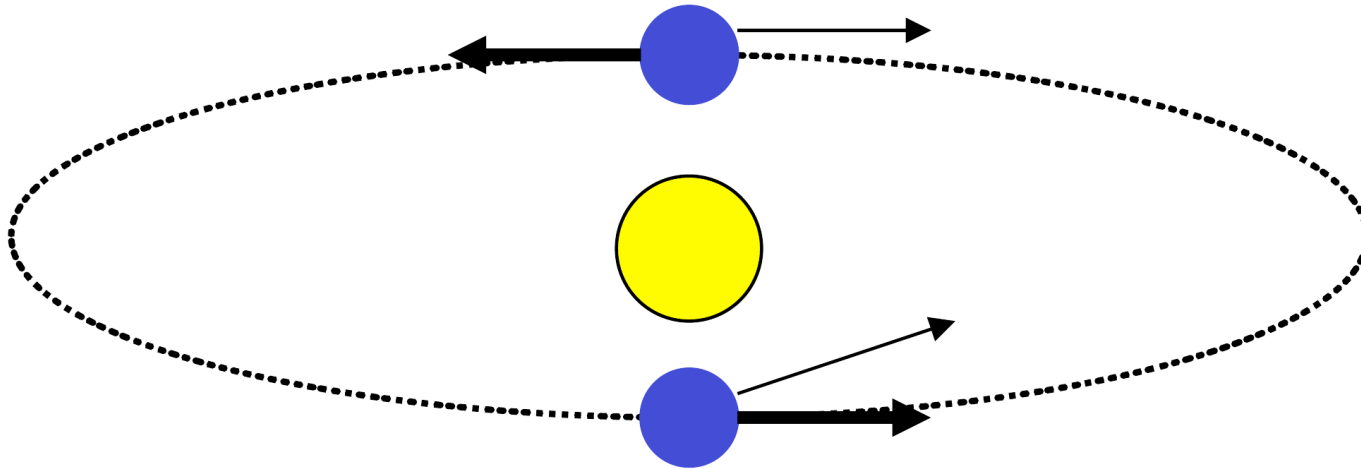
m_p in Jupiter masses, m_s in solar masses, P in years, V in m/s

Exercise for the reader: Derive this!

Radial Velocity Amplitude of Sun due to Planets in the Solar System

Planet	Mass (M_J)	V (m/s)
Mercury	1.74×10^{-4}	0.008
Venus	2.56×10^{-3}	0.086
Earth	3.15×10^{-3}	0.089
Mars	3.38×10^{-4}	0.008
Jupiter	1.0	12.4
Saturn	0.299	2.75
Uranus	0.046	0.297
Neptune	0.054	0.281

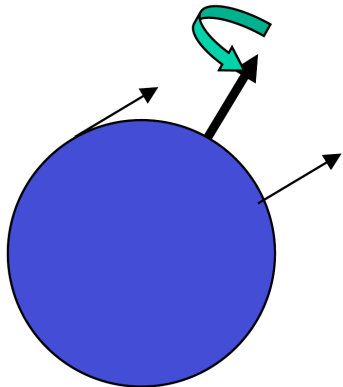
Barycentric correction



Need to know:

- Position of star
- Earth's orbit
- Exact time

Earth's orbital motion can contribute ± 30 km/s (maximum)



Need to know:

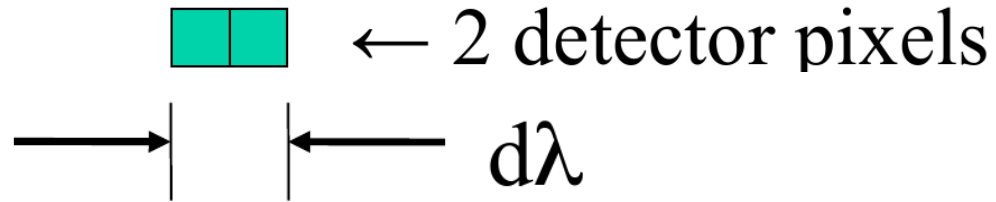
- Latitude and longitude of observatory
- Height above sea level

Earth's rotation can contribute ± 460 m/s (maximum)

Ingredients for Precision Radial Velocities

1. High spectral resolution
 - Easier to detect a Doppler Shift
 2. Large wavelength coverage
 - More spectral lines for a measurement
 3. High Signal-to-noise ratio data
 - High quality data
 4. Simultaneous wavelength calibration
 - Eliminating instrumental shifts
-

High spectral resolution



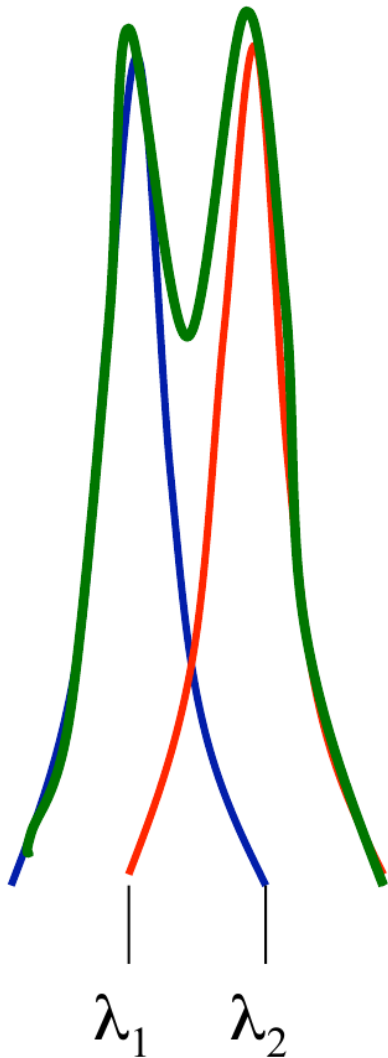
Consider two monochromatic beams

They will just be resolved when they have a wavelength separation of $d\lambda$

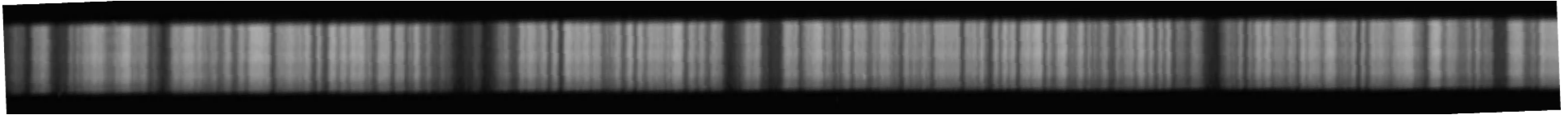
Resolving power:

$$R = \frac{\lambda}{d\lambda}$$

$d\lambda$ = full width of half maximum of calibration lamp emission lines

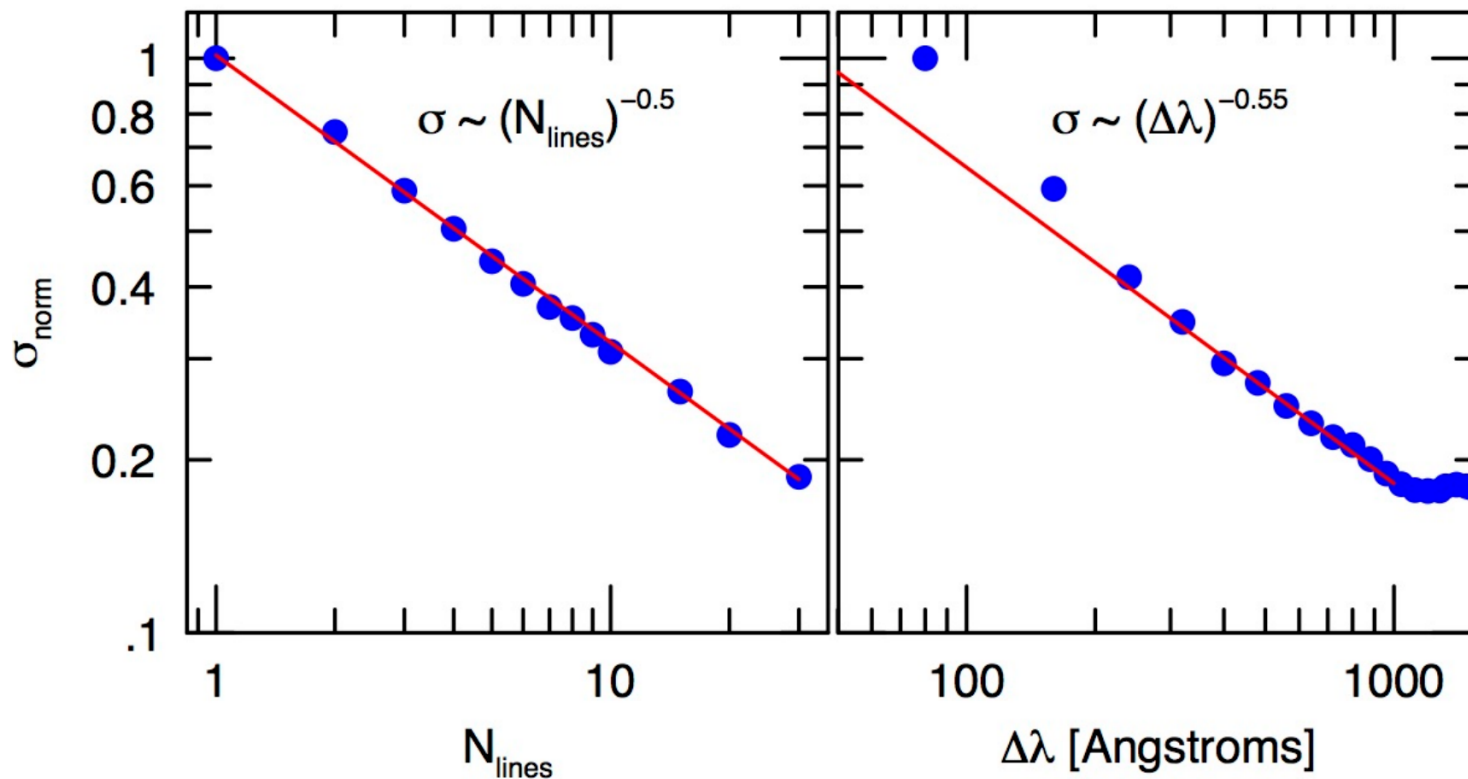


Large Wavelength Coverage

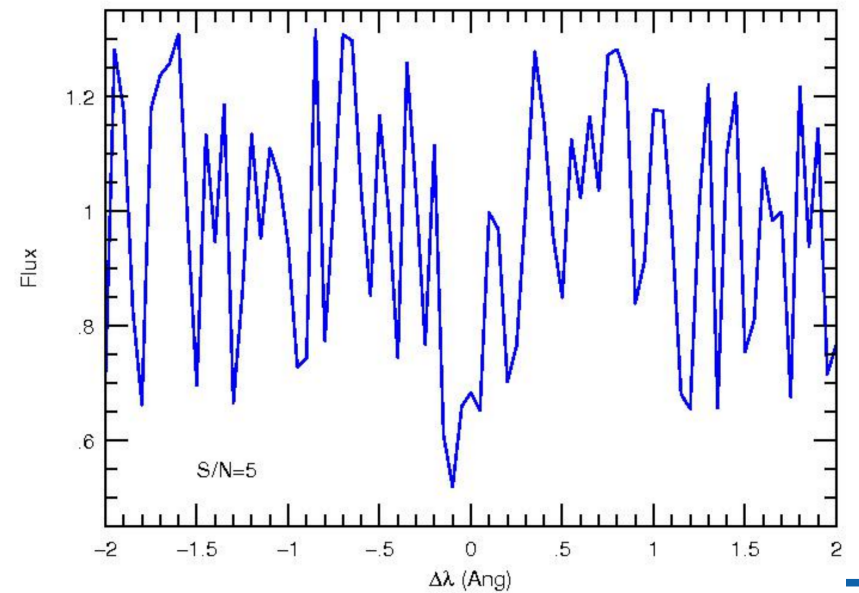
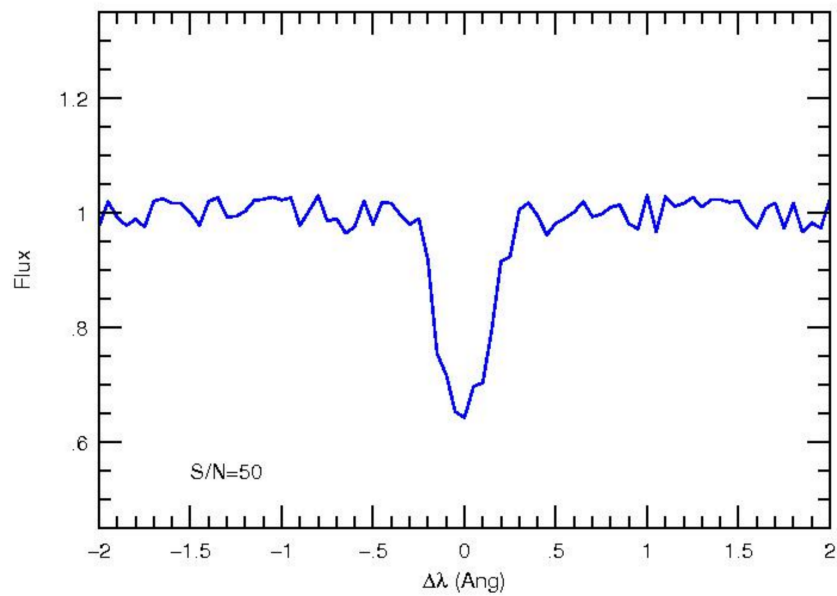
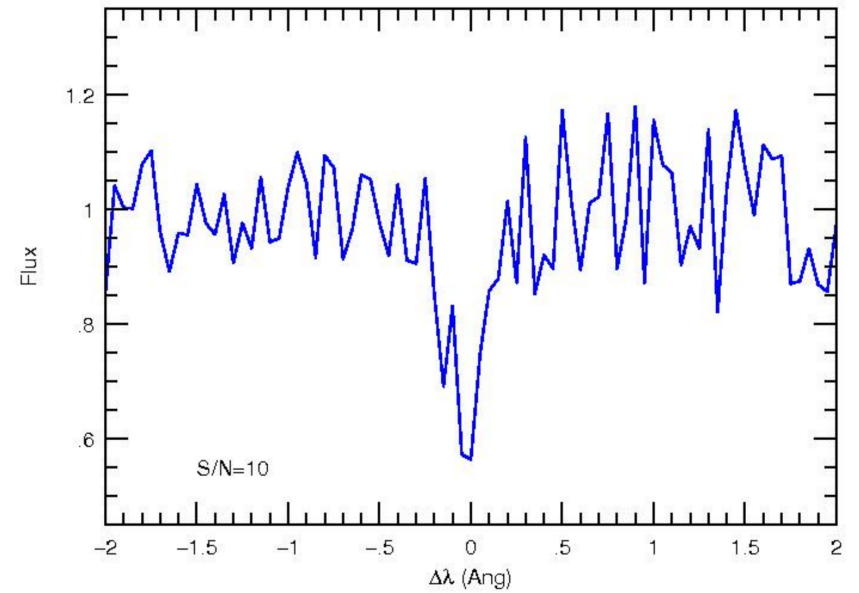
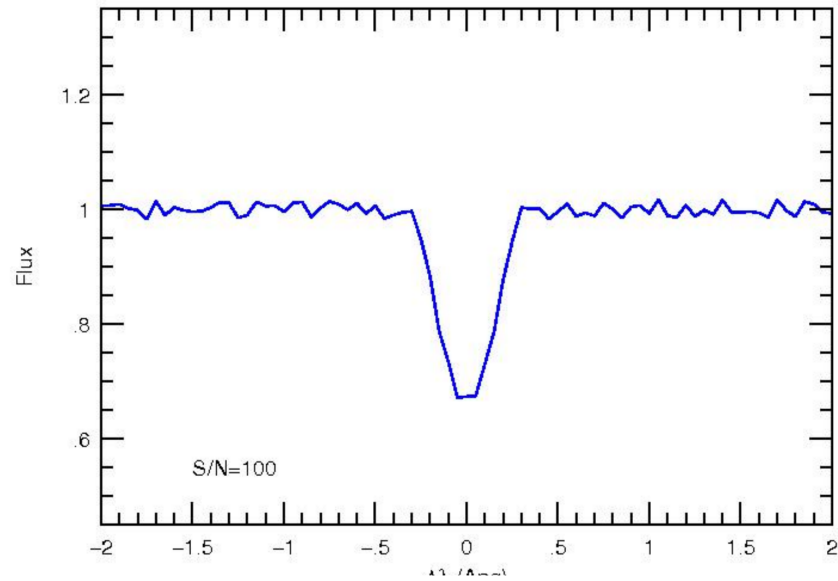


- Each line gives you a measurement of the Doppler shift with an error
- Use 100 lines and your error is 10 times lower

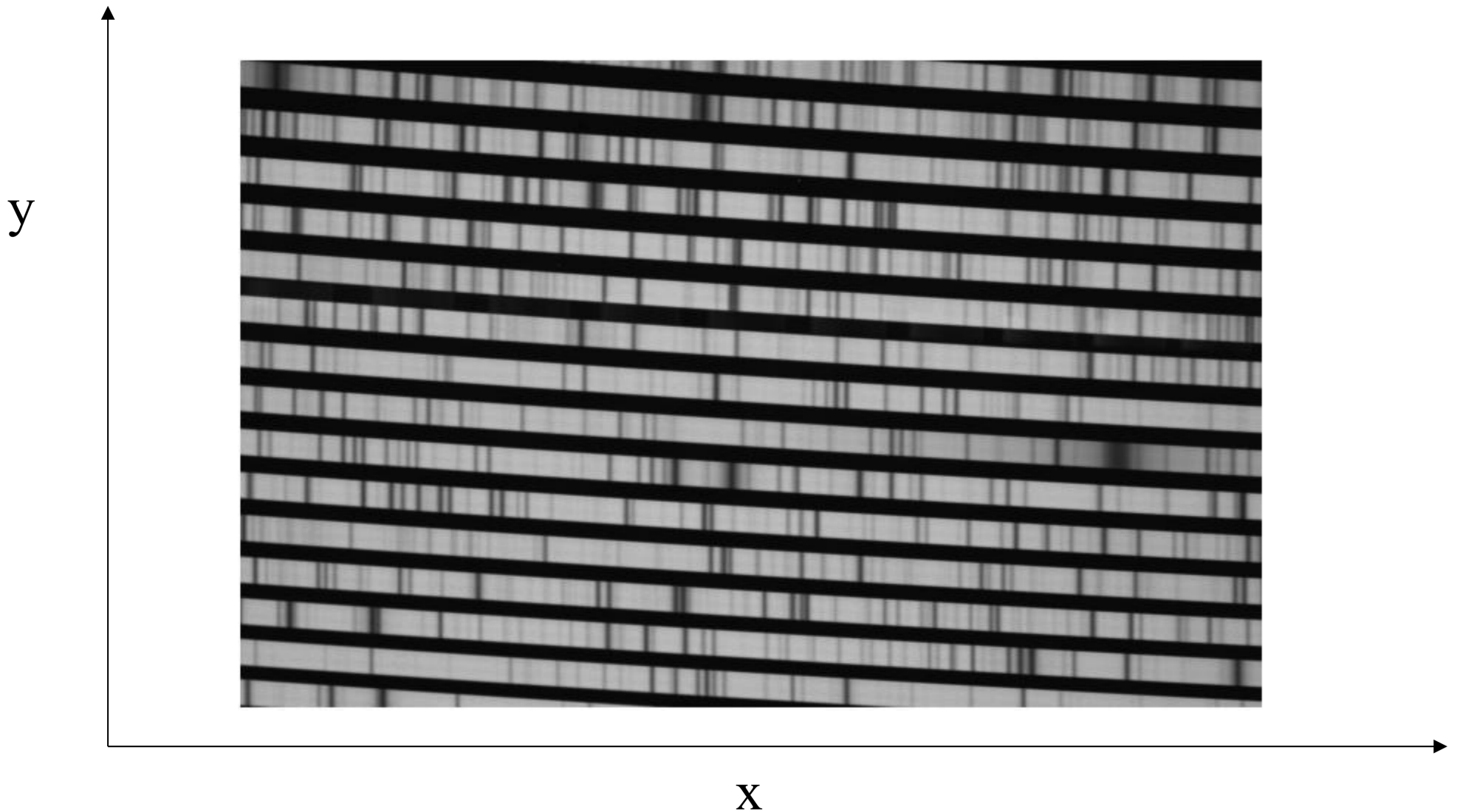
RV error is proportional to $1 / \sqrt{N_{\text{lines}}}$



Influence of the noise

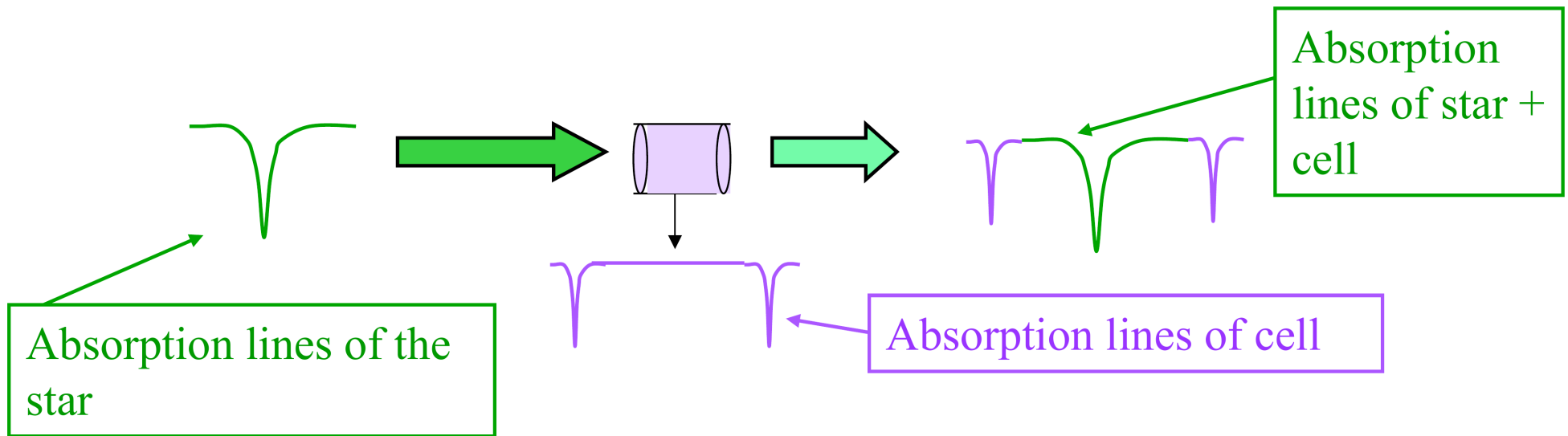


Wavelength calibration



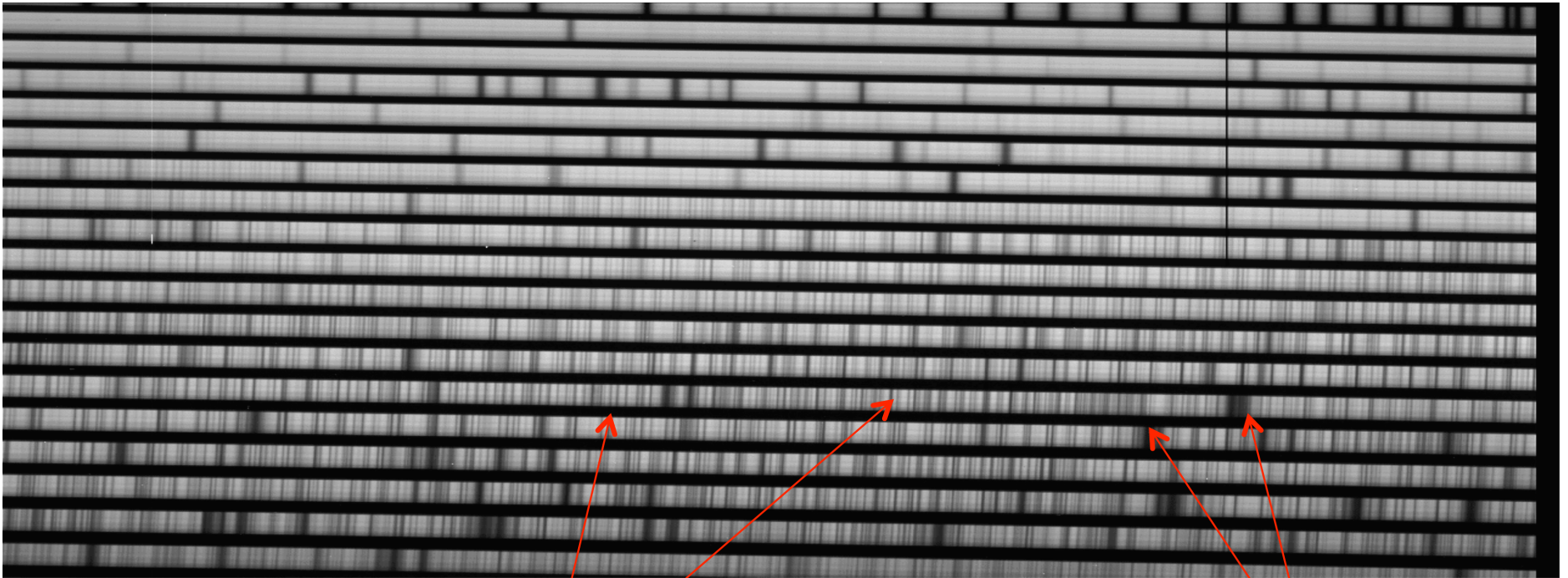
On a detector we only measure x- and y- positions, there is no information about wavelength. For this we need a calibration source

Solution 2: Gas Absorption Cells



Solution 2: Gas Absorption Cells – Iodine

Star observed through an Iodine cell



Iodine lines

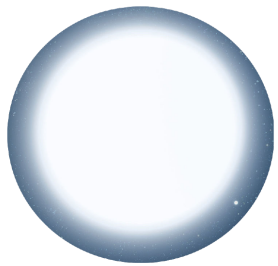
Stellar lines

one high S/N spectrum without Iodine cell necessary for comparison, rest of measurements through Iodine cell → more details in Jana's talk about VIPER

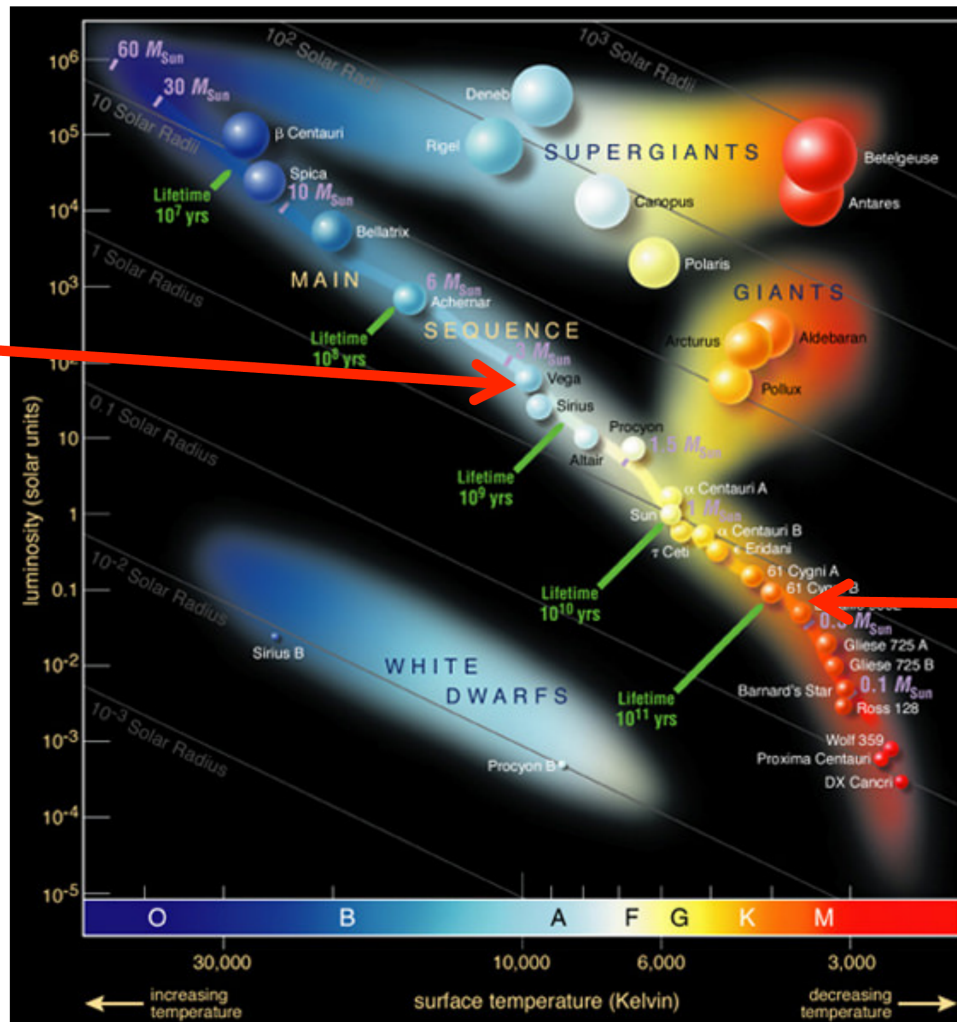
Radial velocity accuracy for different kind of stars

With different kind of stars you can reach different RV accuracy

A-type



$T = 10000\text{ K}$
Rotational
velocity ~ 200
km/s



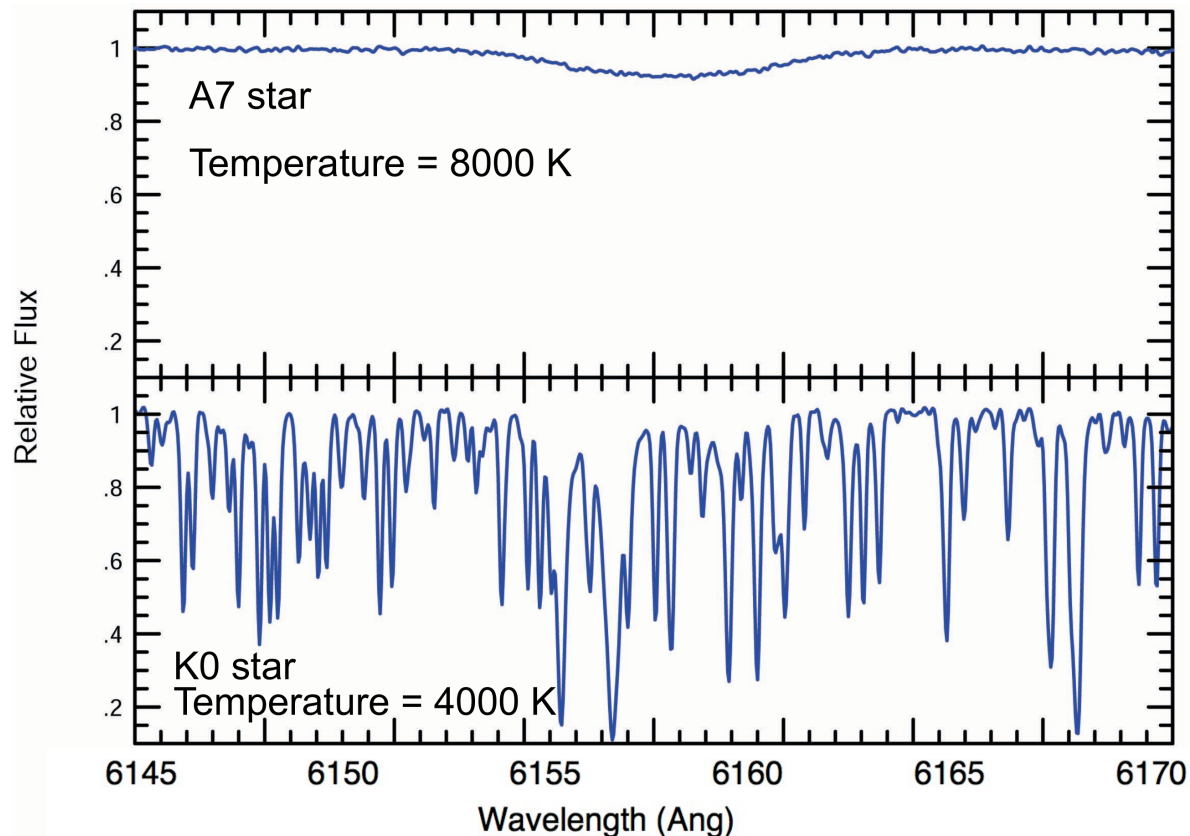
K-type



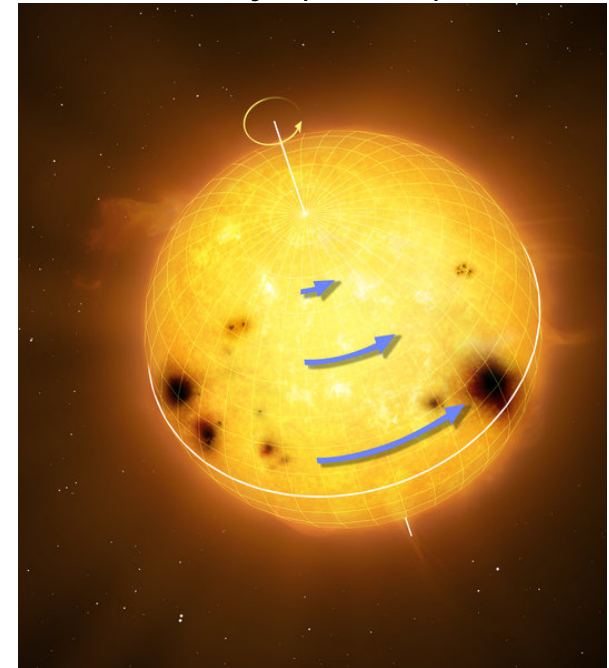
$T = 4500\text{ K}$
Rotational
Velocity $\sim 3\text{ km/s}$

Radial velocity accuracy for different kind of stars

Early-type stars have few spectral lines (high effective temperatures) and high rotation rates.



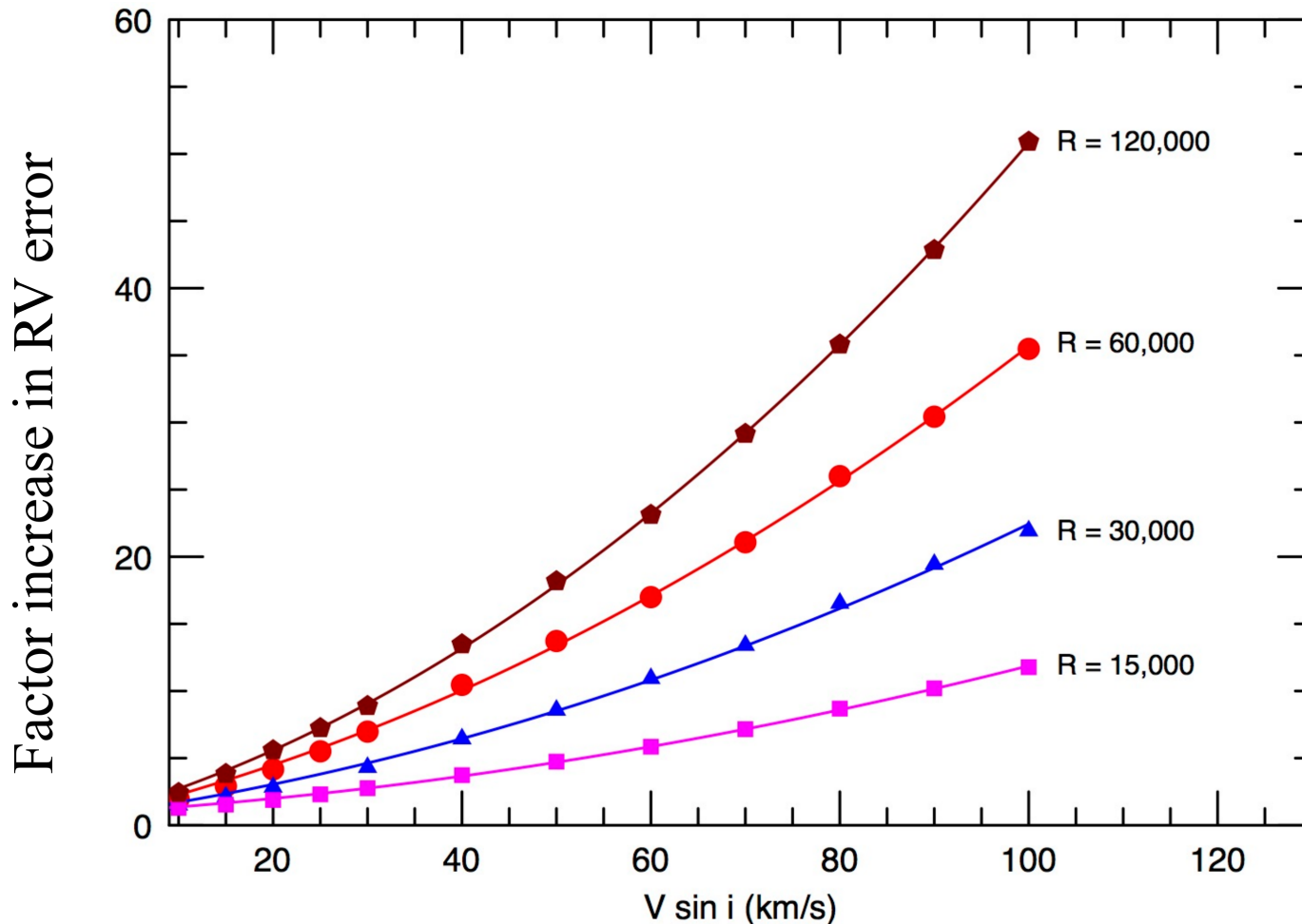
From Gray (1982)



Projected rotational
velocity = $v_{\text{rot}} \times \sin i$
(spin axes of star)

Radial velocity accuracy for different kind of stars

Increase in Error with Stellar Rotation ($v \sin i$)

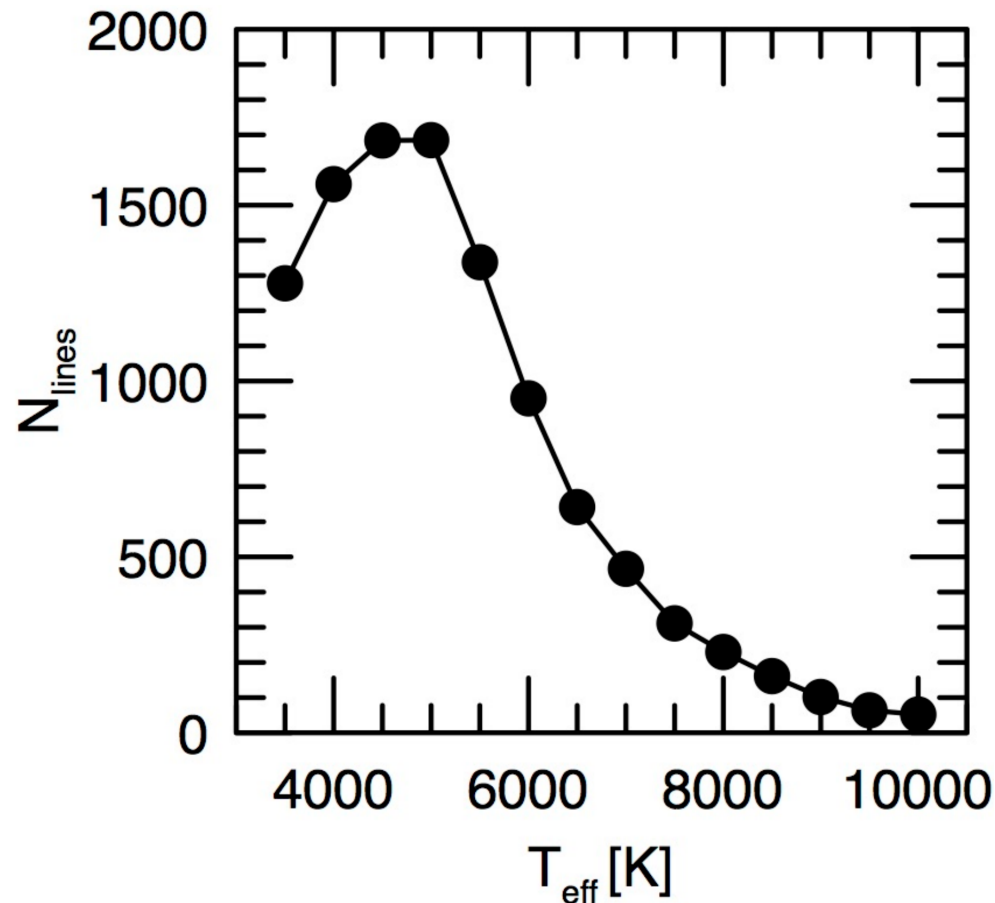


Using $R = 60,000$ for two stars with the same temperature: One rotating at 100 km/s will have an error 35 times greater than a star rotating at 2 km/s

Spectral type	Rotational velocity [km/s]
O4	110
O9	105
B5	108
A0	82
A5	80
F0	44
F5	11
G0	4
G5	3
K0	3
K5	2
M0	10
M4	16
M9	10

Radial velocity accuracy for different kind of stars

Decrease in number of (useful) lines with Effective Temperature



A star with $T_{\text{eff}} = 8000$ K will have nearly 9 times less useful spectral lines than a star at $T_{\text{eff}} = 5000$ K. The RV measurement error for the hot star will be ~ 3 times greater

Radial velocity accuracy for different kind of stars

Including dependence on stellar parameters

$$\sigma(\text{m/s}) = 8.2 \times 10^9 \times (S/N)^{-1} R^{-1.2} (\Delta\lambda)^{-1/2} f(V) g(T)$$

$f(V)$ and $g(T)$ are the effects due to the star

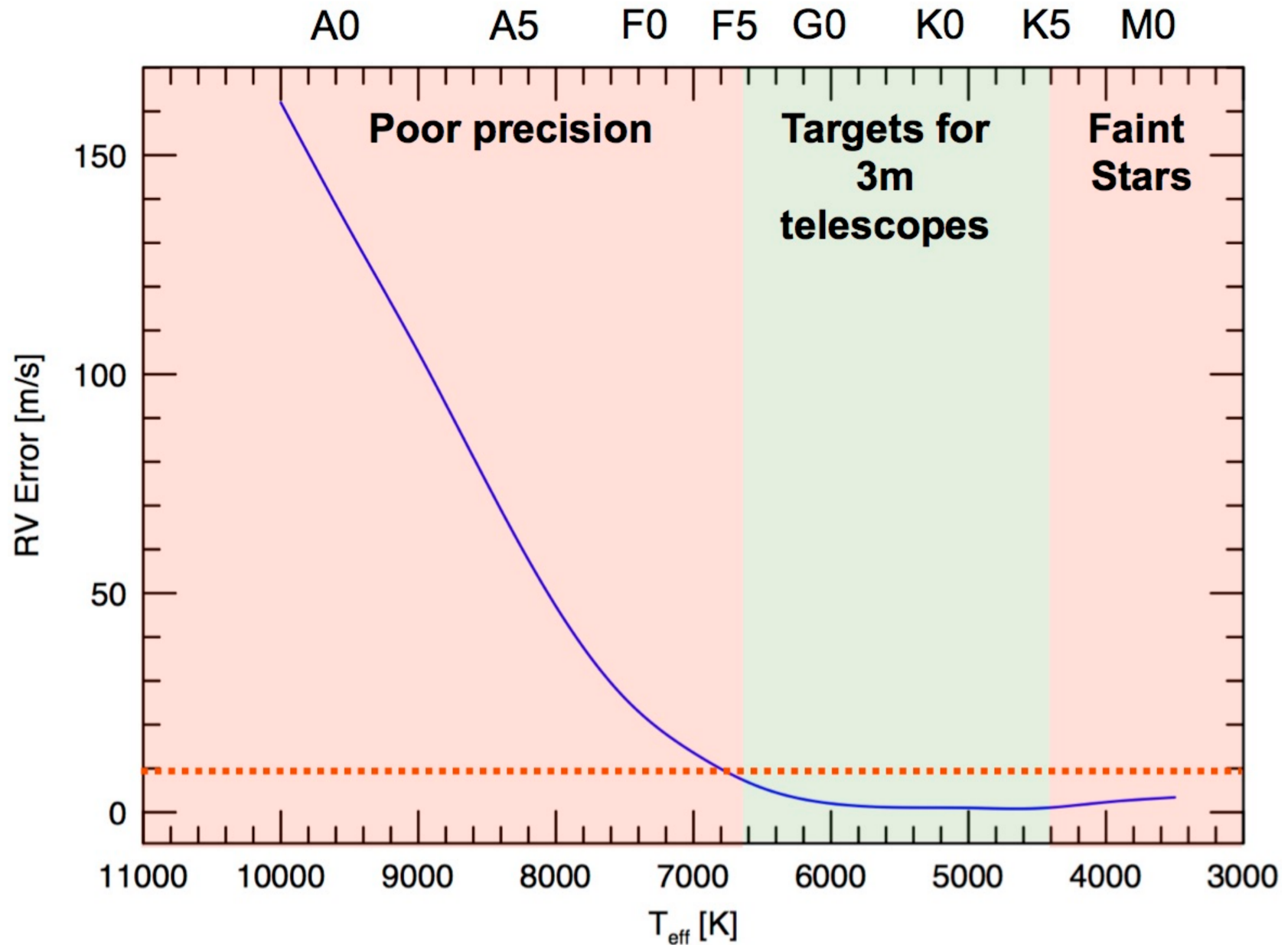
$$f(V) = 0.62 + (0.21 \log R - 0.86)V + (0.00260 - 0.0103)V^2$$

With R = resolving power of spectrograph and V = rotational velocity of the star ($v \sin i$) in km/s

$$g(T) = 0.16e^{1.79(T/5000)}$$

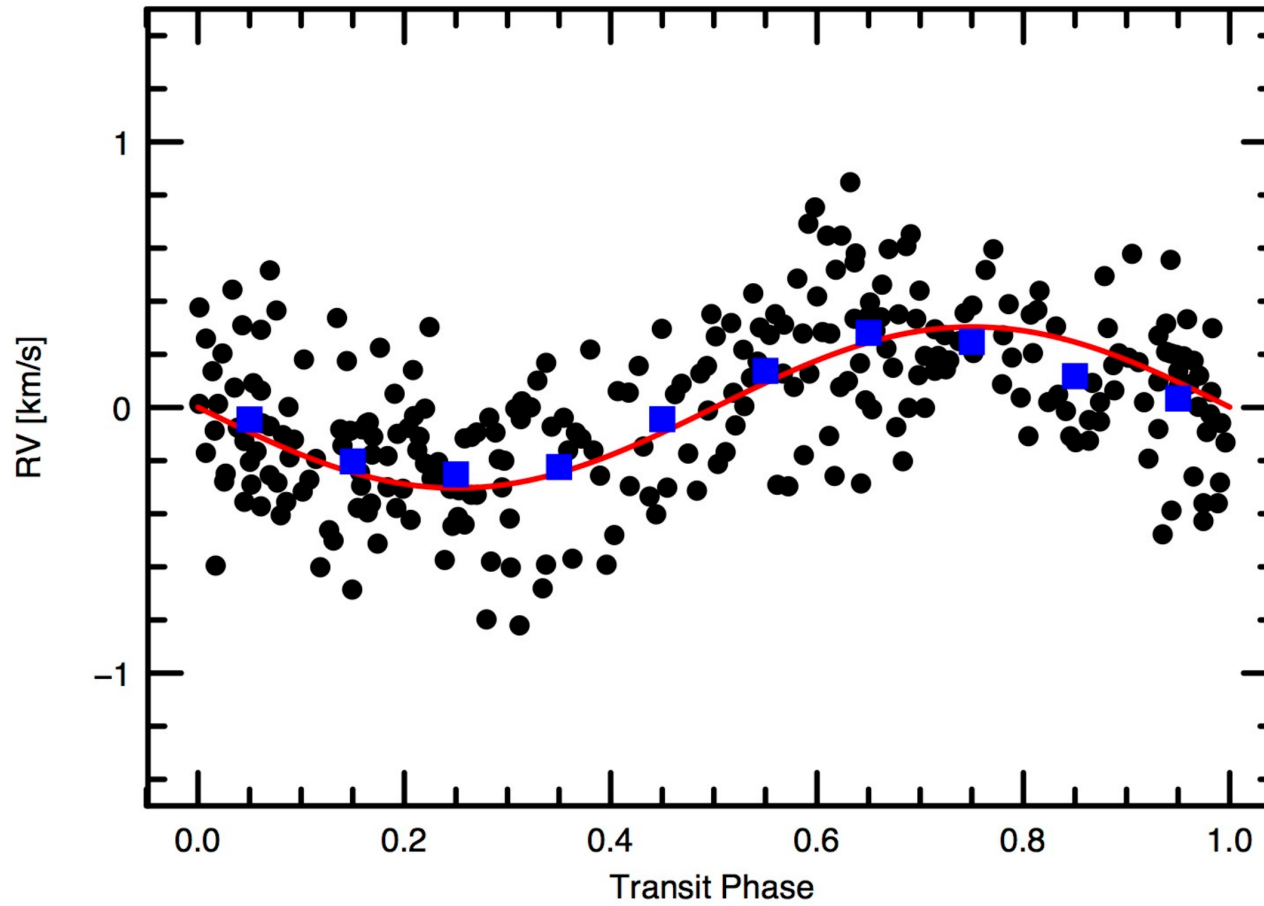
T = effective temperature of the star

The "sweet spot" for RV measurements



Increase accuracy of RV measurements

Just take lots of measurements!



WASP-33b:

- Transiting Planet
- A5 Star
- $T = 8100 \text{ K}$, $v_{\text{rot}} = 90 \text{ km/s}$

Follow-up of exoplanets

7047 confirmed planets:

- spectroscopic follow-up to determine/improve mass determination of the exoplanet
- strategy to find best targets (from www.exoplanet.eu)
 - stellar magnitude (< 11 mag)
 - orbital period
 - accuracy of spectrograph
 - RV amplitude
 - Visibility: observations from 3 UT (5 am)
- important to cover the orbital period with enough data points

Project:

- ⇒ Do spectral follow-up of a hot Jupiter using Platospec at the E152m telescope in La Silla with an Iodine cell (> 3 -5 m/s accuracy)
 - ⇒ Determine RVs
 - ⇒ Fit RV curve
 - ⇒ Derive stellar parameters/ mass
 - ⇒ Determine (minimum) planet mass
-

Determining periods - Fourier transformation

```
import matplotlib.pyplot as plt
import numpy as np
import math
#you'll probably need to install the following two packages
#e.g. with "pip3 install astropy"
import astropy
import lightcurve as lk

#read-in data and convert to lightcurve format
data=np.loadtxt('data.txt')
lc=lk.LightCurve(time=data[:,0],flux=data[:,1],
flux_err=data[:,2])

#Lomb-Scargle periodogram to determine most likely period
pg=lc.to_periodogram(oversample_factor=100,minimum_period=0.1,
maximum_period=10,normalization='amplitude',ls_method='auto')
```

Determining periods - Fourier transformation

```
ax1=pg.plot(view='period')  
print('period:',pg.period_at_max_power.value)
```

```
#Phase-fold RV curve
```

```
period=pg.period_at_max_power.value
```

```
#period from highest peak in Lomb-Scargle
```

```
lc_fold=lc.fold(period,epoch_time=0.0)
```

```
#save phase-folded RV curve
```

```
x=lc_fold.time.value/period
```

```
y=lc_fold.flux
```

```
yerr=lc_fold.flux_err
```

Fitting RVs using RadVel

RadVEL – The Radial Velocity Fitting Toolkit (example control file, data)

Parameters:

- *starname* – name of star
 - *nplanets* – Number of planets
 - *instnames* – list of instruments
 - *pern* – orbital period of nth planet
 - *tcn* – time of inferior conjunction
 - *en* – eccentricity
 - *wn* – argument of periastron
 - *kn* – velocity semi-amplitude
 - *gamma_x* – velocity zero-point for instrument x
 - *jit_x* – jitter for instrument x
 - `params["param"].vary = False` – keep parameter fixed while fitting
 - *priors* – set limits for parameters
 - `stellar = dict(mstar=1.12, mstar_err= 0.05)` – stellar mass
-

Fitting RVs using RadVel

- maximum-likelihood fit

radvel fit -s control_file.py

- plot best-fit solution

radvel plot -t rv -s control_file.py

- perform Markov-Chain Monte Carlo (MCMC) exploration to assess parameter uncertainties

radvel mcmc -s control_file.py

- update plot with MCMC results

radvel plot -t rv corner trend -s control_file.py

- combine fit of RV time-series with properties of host star

radvel derive -s control_file.py

- plot of derived parameters

radvel ic -t nplanets e trend -s control_file.py

Modeling the Rossiter-McLaughlin Effect

starry: `https://starry.readthedocs.io`

Approximating the light curve

#download lightcurve from TESS

```
import numpy as np
```

```
np.int = np.int32
```

```
np.float = np.float64
```

```
np.bool = np.bool_
```

```
import lightcurve as lk
```

```
target='HD2685'
```

```
search_lightcurve = lk.search_lightcurve('%s'%(target),  
                                          exptime=120,author='SPOC').download_all()
```

```
flux=search_lightcurve.stitch()
```

Approximating the light curve

#BLS Algorithmus

```
period = np.linspace(pmin, pmax, 10000) #trial periods
duration = np.linspace(dur_min,dur_max,1000) #trial durations
# Create a BLSPeriodogram
bls = flux.to_periodogram(method='bls', period=period,
                          duration = duration, frequency_factor=500000);
#print results
planet_b_period = bls.period_at_max_power
planet_b_t0 = bls.transit_time_at_max_power
planet_b_dur = bls.duration_at_max_power
planet_b_dep = bls.depth_at_max_power
print(planet_b_period,planet_b_t0,planet_b_dur,planet_b_dep)
```

Approximating the light curve

#plot data and model

```
model_lc = bls.get_transit_model(period=planet_b_period,
                                  duration=planet_b_dur,
                                  transit_time=planet_b_t0)
ax=flux.fold(planet_b_period,epoch_time=planet_b_t0).
plot(color='b')
plt.xlim(-0.1*planet_b_period.value,0.1*planet_b_period.value)
model_lc.fold(planet_b_period,epoch_time=planet_b_t0).bin(
    time_bin_size=binsize).plot(ax=ax)
```